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Designing Pitch Controller for Large Wind Turbines via LMI Techniques

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Abstract

This paper proposes a design of robust LMI-based collective pitch controllers (CPC) for large wind turbines operating above their rated wind speeds. The proposed controller design takes into account model uncertainties by designing a controller based on a polytopic model. The LMI-based approach allows additional constraints to be included in the design (e.g. H_∞ problem, H_2 problem, H_2/H_∞ trade-off criteria, and pole clustering).These constrains are exploited to include requirements for perfect regulation, efficient disturbance rejection, and permissible actuator usage. The proposed controller is combined with individual pitch controller (IPC) that reduces the periodic blade's load by alleviating once per revolution (1P) frequency fatigue loads.

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Keywords: Pitch control, individual blade pitch, LMI

1. Introduction

The use of wind power is increasing rapidly. At the same time the need for better cost effectiveness of wind power plants has stimulated growth in wind turbines' size and power. In above rated wind conditions, the goals for turbine operation change from control of generator torque for maximum power tracking to those of regulating power at rated levels with mitigating fatigue loading on the turbine structure. An ordinary PI pitch controller regulates the generator speed without taking into consideration the unstructured dynamics of the blades, the drivetrain nor the tower. Further, the nonlinear variation of rotor torque with wind speed and the pitch angle presents a challenging problem. Moreover, the pitch actuator in large wind turbines always has restricted operating limits on pitch angle and pitch rate [1].The previous reasons motivate the need for a robust pitch controller that regulates the generator speed at different operating points. This controller must take into account all the previous constrains. In this paper,

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a multi objectives pitch controller will be designed using LMI techniques combined with IPC.
When the turbine blade sweeps, it experiences changes in wind speed due to wind shear, tower shadow, yaw misalignment and turbulence. These variations lead to (1P) large component in the blade loads, it's now essential to design (IPC) to cancel this component [2].

Pitch controller is designed using H_∞ technique in [3], [4], the main objective is to regulate the speed by improving the disturbance rejection. The required control effort for this isn't considered in design. In [5], it is proposed to design gain scheduled feedback /feed forward CPC for speed regulation combined with IPC for load reduction. Also in [6], optimal LQG feedback /feed forward CPC is proposed for speed regulation combined with IPC for load reduction. Combined CPC with IPC is proposed in [7] both as PI controllers. In [5], [6], and [7] the controller design is based on a single linearized model. A multi objective (H_2/H_∞) pitch controller is proposed in [8].It doesn't consider improving the transient response at different operating points. This proposed paper considers an LMI based pitch controller. The design includes H_∞ problem for better speed regulation, H_2 problem for optimizing control action with performance, H_2/H_∞ trade-off criteria for the optimization of the two problems, and pole clustering for improving transient response. The controller is based on a polytopic model to overcome model uncertainty at different operating points. The proposed controller is combined with IPC to mitigate mechanical fatigue loads.

In section (II), the turbine model will be explained. In section (III) the proposed CPC controller is designed in two phases. First, designing state feedback controller via LMI techniques based on a single design model. Second, designing CPC based on a polytopic model. In section (IV), the design of IPC will be discussed. It's a PI controller used to cancel the fatigue loads affecting the turbine. The simulation result comparing the proposed controller and the conventional PI controller is shown in section (V), finally the conclusion in section (VI).

2. Model Description

Simulations are performed on a full non-linear turbine model provided by the FAST (Fatigue, Aero-dynamics, Structures, and Turbulence) software code developed at the US National Renewable Energy Laboratory (NREL) [9]. The model used is a 3-bladed, variable speed 5 MW wind turbine model with the following specifications in table1:

Table 1: Wind turbine specifications

Hub height	90 meter
Blade diameter	126 meter
Cut in, Rated, cut out wind speed	3 m/s , 11.4 m/s, 25 m/s
Cut in, Rated rotor speed	6.9 rpm, 12.1 rpm
Rated generator speed	1173.7 rpm

More specifications could be found in [10]. The pitch actuator is modeled by a second order system. The permissible pitch angle ranges from 0 to 90° with maximum rate of 8°/s. Only the following degrees of freedoms (DOFs) are enabled in our model:

a- Generator DOF: q_1.
b- Drivetrain rotational-flexibility DOF: q_2.
c- First flapwise blade mode for each blade DOF: q_3, q_4, q_5
d- Fore-aft tower bending-mode DOF: q_6.

where q_I denotes the displacement of DOF number (I), each DOF could be presented in linearized model according to this equation:

$$M\Delta\ddot{q}_I + C\Delta\dot{q}_I + K\Delta q_I = F * u + F_d * u_d \tag{1}$$

where M, C, K, F, F_d, u, and u_d denote mass matrix, stiffness matrix, damping matrix, control input matrix, wind input disturbance matrix, control input vector, and disturbance input vector respectively. Figure 1 shows the synthesis of FAST model used in simulation:

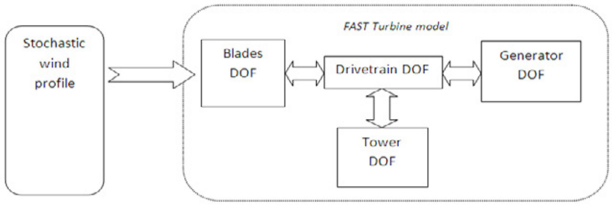

Fig. 1. FAST model synthesis

The generator torque has four control regions: 1, 2, 2½, and 3. Region (1) is a control region before cut-in wind speed with zero generator torque and no power is extracted from the wind. Instead, the wind is used to accelerate the rotor for start-up. The main task in Region (2) is optimizing power capture by maintaining a constant (optimal) tip-speed ratio (λ=λ0), while the pitch angle is kept zero. In Region (3), the wind speed is above rated speed. The generator controller task is to hold the generator torque constant, in the mean the pitch controller regulates the generator speed at the rated value in order to capture the rated power. Region (2½) is a linear transition between Regions 2 and 3 used to limit tip speed (for less noise emissions) at rated power. The torque speed response of the model is shown in Figure 2.

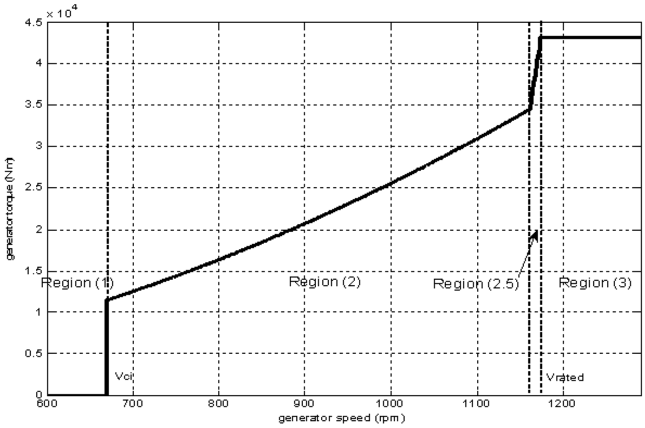

Fig. 2. Torque speed characteristics of the generator

3. Designing CPC via LMI

The proposed technique is to design state feedback collective pitch controller (CPC) to regulate the generator speed. It is based on LMI techniques. This controller is combined with IPC that mitigates the flapwise moment by cancelling (1P) frequency. The proposed control strategy is shown in Figure 3.
where $M_{1,2,3}$ are the blade tip flapwise moments of each blade. ω_{gen}, T_{gen} are the generator's speed and torque. The total control action (β) is calculated as follow:

$$\beta = \beta_{ipc} + \beta_{cpc} + \bar{\beta} \tag{2}$$

where ($\bar{\beta}$) is the pitch angle operating point, it's calculated by changing operating point with wind speed through a look up table. The generator speed is regulated by the control action (βcpc). The flapwise moment is reduced by the control action (βipc).

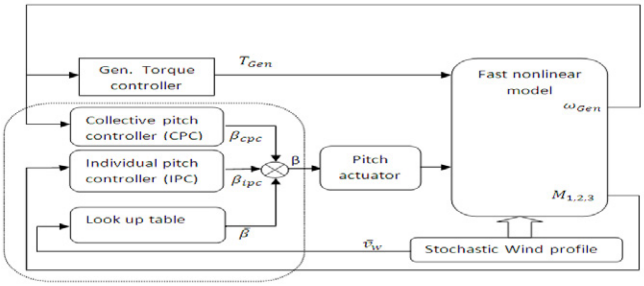

Fig. 3. The pitch controller synthesis

CPC objectives are:

1- Efficient disturbance rejection for best speed regulation. This could be achieved by maintaining the RMS gain of $T(s)_\infty$ (H_∞ norm) below pre-defined value (γ_0; γ_0>0), where $T(s)_\infty$ is the closed loop transfer function from W to Z_∞, where($Z_\infty = \Delta\omega_{gen}$) represents the regulation error due to disturbance (W): (H_∞ problem) [11].

2- Trade-off capability between the control effort and the performance, which done by maintaining the (H_2 norm) of $T(s)_2$ (LQG Cost) below predefined value (ν0; ν0>0), where $T(s)_2$ is the closed loop transfer function from W to Z_2, where ($Z_2=Q*\Delta x+R*\Delta u$) presents the tradeoff criteria between the perturbations in states, and the control action: (H_2 problem) [12].

3- Optimization of the two previous problems via (H_2/H_∞ trade off criteria) which minimize the objective function f:

$$f = \alpha\|T_\infty\|_\infty^2 + \beta\|T_2\|_2^2 \tag{3}$$

4-good transient response by maintaining the closed loop poles inside a particular region D (pole clustering problem).

CPC is a state feedback controller. Some states are not measurable, so an optimal observer (kalman filter) is designed based on [13]. The controller structure is shown in Figure 4.

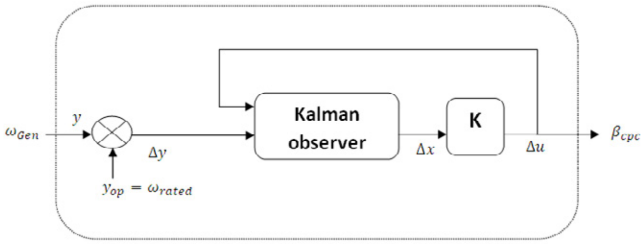

Fig. 4 CPC synthesis

3.1. Designing CPC based on a Single Design Model

In order to design an LMI controller, a linearized LTI design model must be available. FAST can provide a linearized model at certain operating point $(\bar{\omega}_{gen}, \bar{\beta}, \bar{v}_w)$ [9], where $\bar{\omega}_{gen}$ is the generator speed, $\overline{\beta}$ is the pitch angle, and $\overline{v}_w$ is the hub height wind speed. In our design model, the enabled DOFs are the generator, and the drive train flexibility, as these are only observable states from the measured generator speed. The linearized model takes the form:

$$P(S):\begin{cases}\Delta\dot{x} = A\Delta x + B\Delta u + B_d\Delta u_d & (4)\\ \Delta y = C\Delta x + D\Delta u + D_d\Delta u_d & (5)\end{cases}$$

where $\Delta x= [\Delta x_1,\Delta x_2,\Delta x_3]$;

Δx_1: Drivetrain rotational-flexibility (perturbations in Drivetrain torsional displacement); (m)

Δx_2: generator DOF (perturbations in rotor speed); (rad/s)

Δx_3: Drivetrain flexibility (perturbations in Drivetrain torsional velocity); (m/s)

$\Delta u=\Delta\beta$, Δu is the perturbation in the collective pitch (control action), $\Delta u=\Delta v_w$ is the perturbation in the wind speed. $\Delta y=\Delta\omega$, $\Delta\omega$ is the perturbation in generator speed. The design model p(s) is completely observable and completely controllable. It's a linearized model around the operating point $(\overline{\omega}_{gen} = \omega_{rated} = 1173.6\ rpm, \bar{\beta} = 14.93°, \bar{v}_w = 18\ m/s)$. The model could be written in the following form:

$$P(S):\begin{cases}\Delta\dot{X} = A * \Delta X + B_1 * \Delta W + B_2 * \Delta u & (6)\\ Z_\infty = C_1 * \Delta X + D_{11} * \Delta W + D_{21} * \Delta u & (7)\\ Z_2 = C_2 * \Delta X + D_{22} * \Delta u & (8)\end{cases}$$

where ($Z_\infty=\Delta y=[\Delta\omega_{gen}]$) presents the regulation error due to disturbance (W), and ($Z_2=Q*\Delta x+R*\Delta u$) , Where Q=diag ($Q_1,Q_2,Q_3$), R present the weighting matrices of LQG cost function (J):

$$J = \int_0^\infty Q^2 * \Delta X^2 + R^2 u^2 \qquad (9)$$

The LQG optimal problem could be a perfect tool for good comparison between performance and control action. The state feedback controller takes the form:

$$\Delta u=\beta_{cpc}=K*\Delta X \qquad (10)$$

Design model synthesis is shown in Figure 5.

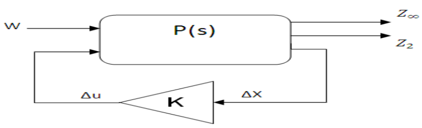

Fig. 5. Structure of design model

The LMI problem takes the formulation:

$$minimize\ (\alpha * \gamma^2 + \beta * Trace(Q))$$

Subject to:

$$\begin{cases} H_\infty\ performance: \left\{\begin{pmatrix} AP + PA^T + B_2Y + Y^TB_2^T & B_1 & PC_1^T + Y^TD_{12}^T \\ * & -I & D_{11}^T \\ * & * & -\gamma^2 I\end{pmatrix} < 0\right. & (11)\\ H_2\ performance: \begin{cases}\begin{pmatrix} Q & C_2P + D_{22}Y \\ * & P\end{pmatrix} > 0 & (12)\\ Trace(Q) < v_0^2 & (13)\\ \gamma^2 < \gamma_0^2 & (14)\end{cases}\\ pole\ clustering: \{\pi \circledast P + \Gamma \circledast (P * A_{cl}) + \Gamma^T \circledast (A_{cl}^T * P) < 0 & (15)\end{cases}$$

where P is a Lyapunov matrix that satisfies all the previous constrains, (*) denotes symmetrical element, ($\circledast$) denotes the kroneker product, A_{cl} is the state matrix of the closed loop system. (Γ, π) are the parameters matrices of the desired pole clustering region. Further details and proves are mentioned in [12], [13]. When a feasible solution for the LMI framework is reached, we will reach the optimal value of cost function (3). The solution yields (P, Y*, γ*, Q*), where γ* is the optimal H_∞ performance, and Q* is the optimal H_2 performance. This is a semi definite programming problem (SDP) solved by LMI Lab solver in LMI control toolbox [14].The final state feedback controller is calculated as:

$$K = Y^* * (P)^{-1} \tag{16}$$

This controller should guarantee that,

$\|T_\infty\|_\infty < \gamma_0, \|T_2\|_2 < \sqrt{\mathrm{Trace}(Q*)}$, and $A_{cl} \in D$,

γ_0 represents the worst case of the desired RMS gain of the system. It is chosen to get better disturbance rejection. ν_0 represents the worst case of the desired H_2 norm. It's the norm of the LQG optimization problem which used to get a tradeoff between control effort and performance. (ν_0, γ_0) are chosen as small as possible as long as a feasible solution is found. These values were chosen as (γ_0=17.3, ν_0=1) .

Pole clustering regions must guarantees improvement in transient response. This could be done by choosing three constrains here, the first region (R1) will guarantee an upper limit on settling time, the second region (R2) will be chosen to prevent excessive control action. Finally, region three (R3) is chosen as an upper bound on damping ratio. LMI regions are convex subsets D of the complex plane characterized by is defined by [15]:

$$D = \{z \in c : \pi + \Gamma z + \Gamma^T \bar{z} < 0\} \tag{17}$$

(R1), and (R2) regions are defined by a vertical strip between (h_1, h_2) with characteristic function ($F_{D1,2}$) as:

$$F_{D1,2}(Z) = \begin{pmatrix} 2h_1 - (z - \bar{z}) & 0 \\ 0 & (z + \bar{z}) - 2h_2 \end{pmatrix} \tag{18}$$

Region (R3) is a conic sector centered at the origin with inner angle (2θ) with characteristic function (F_{D3}) as:

$$F_{D3}(Z) = \begin{pmatrix} \sin(\theta) * (z + \bar{z}) & -\cos(\theta) * (z - \bar{z}) \\ \cos(\theta) * (z - \bar{z}) & \sin(\theta) * (z - \bar{z}) \end{pmatrix} \tag{19}$$

The region parameters are taken as (h_1=-1, h_2=-4, θ=80°). The resulted LMI region (D) is the intersection between the three regions.

The relation between H_2, H_∞ performance is calculated at different weights of the trade off criteria given in (3). By choosing different combinations for the weights (β, α), Figure 6 shows the relation between them:

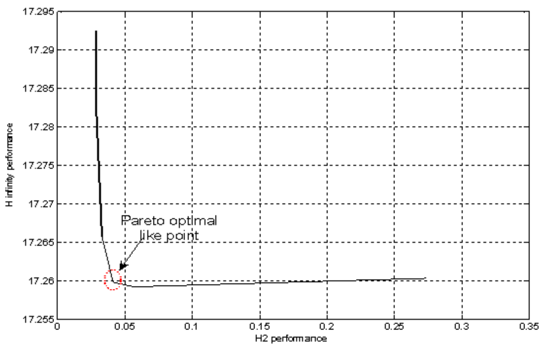

Fig. 6. H2performance vs H∞

The optimal performance occurs at the minimum value of the cost function (3). This value exists as a pareto optimal like point which is highlighted in figure7.This point resulted in optimal weights for the cost function (β=47, α=0.1), so the optimal form of the objective function is:

$$F = 0.1 * \|T_\infty\|_\infty^2 + 47 * \|T_2\|_2^2 \tag{20}$$

Now, the LMI problem could be written in this form:

$$minimize\ f: (f = 0.1 * \|T_\infty\|_\infty^2 + 47 * \|T_2\|_2^2),$$

$$subject\ to \begin{cases} \|T_\infty\|_\infty < 17.3 & (21) \\ \|T_2\|_2 < 1 & (22) \\ closed\ loop\ poles\ (A_{cl}) \in region\ (D) & (23) \end{cases}$$

The resulted controller is: $K = [674.6\ 8.024\ 5.7]^T$. The closed loop poles will be checked at different linearized models derived at different operating points (different wind speeds). Figure 7 shows that the previous controller only manages to keep the eigenvalues inside the desired region (D) at certain operating points. At high wind speeds the closed loop poles are outside this region as the design is based on single design model. This will lead to excessive control action at high wind speed. As a result, the control action may exceed the actuator abilities at these operating points. This excessive action will also amplify the effect of unstructured dynamics (blades, tower, and the platform). This will deteriorate the performance of the system significantly.

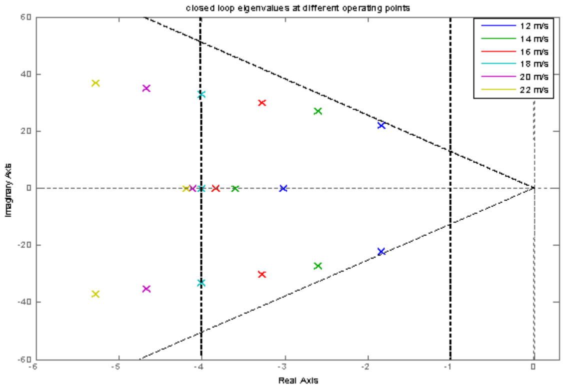

Fig. 7. Closed loop poles in single design model case

The previous results show the need for depending on more than one design model due to model uncertainty, this will fulfill the desired constrains at all different operating points.

3.2. Designing a CPC based on a Polytopic Uncertain System

Six different linearized design models are considered here. These models are linearized models at different operating points, typically at $(\ \bar{v}_w = 12\ m/s, 14\ m/s, 16\ m/s, 18\ m/s, 20\ m/s, 22\ m/s)$ to cover all region (3) range. Each model has different operating point of pitch angle ($\bar{\beta}$), but all models are linearized at the same generator speed which equals rated speed. The general model $P_i(S)$ will be put in the form:

In this case the matrix S(t) lies within a fixed polytope with 6 vertices, the uncertainty set (Ω) is defined as :

$$\Omega = Co\{S_1, S_{2,}, \ldots, S_6\} = \left\{ \sum_{i=1}^{6} \alpha_i S_i : \alpha_i \geq 0, \sum_{i=1}^{6} \alpha_i = 1 \right\} \qquad (27)$$

where Co presents the set of vertices defining the set (Ω), and each model matrix is defined as

$$S_1 = \begin{bmatrix} A_1 & B_{11} & B_{21} \\ C_{11} & D_{111} & D_{121} \\ C_{21} & 0 & D_{21} \end{bmatrix}, \dots , S_6 = \begin{bmatrix} A_6 & B_{16} & B_{26} \\ C_{16} & D_{126} & D_{126} \\ C_{26} & 0 & D_{26} \end{bmatrix}$$

The LMI problem formulation is:

$$minimize\ (\alpha * \gamma^2 + \beta * Trace(Q))$$

Subject to:

$$\begin{cases} H_\infty\ problem: \left\{ \begin{pmatrix} A_i P + P A_i^T + B_{2i} Y + Y^T B_{2i}^T & B_{1i} & P C_{1i}^T + Y^T D_{12i}^T \\ * & -I & D_{11i}^T \\ * & * & -\gamma^2 I \end{pmatrix} < 0 \right. & (28) \\ H_2\ performance: \begin{cases} \begin{pmatrix} Q & C_{2i} P + D_{22i} Y \\ * & P \end{pmatrix} > 0 & (29) \\ Trace(Q) < v_0^2 & (30) \\ \gamma^2 < \gamma_0^2 & (31) \end{cases} \\ pole\ clustering: \{ \pi \odot P + \Gamma \odot (P * A_{cl_i}) + \Gamma^T \odot (A_{cl_i}^T * P) < 0 & (32) \end{cases}$$

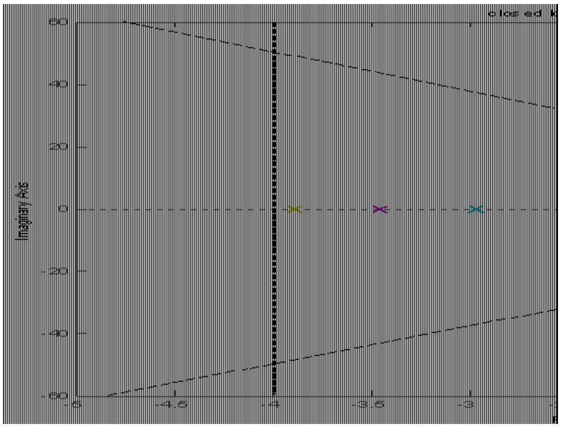

Fig. 8 Closed loop poles in polytopic model case

Here we are seeking for a single quadratic Lyapunov function (P). It should fulfill all the design objectives mentioned in equations (21), (22), and (23) for all plants in the polytope. The control law is the same as equation (16). The resulted controller is: K= [3.5842 2.0471 1.6246]'. The closed loop poles will be checked on different linearized models at different operating points (different wind speeds). Figure 8 shows that the previous controller managed to keep the eigen values inside the desired region (D) at all operating points. This insures that the desired response will be fulfilled at the different operating points.

4. Designing IPC

Lately intensive researches managed to reduce the periodic blade flapwise moment by using periodic pitching technique of the rotor blades (see e.g. [2], [16]). In this approach each of the blades needs to be pitched according to the intermittent loads that it experiences. The spectrum of the blade root bending moment caused by wind shear has a dominant component at frequency 1p while higher harmonics could be damped [17]. However, there are some methods for reduction of higher load harmonics (called higher harmonic control - HHC) which mentioned in [18].At the same time the rotor speed regulation is unaffected due to the decoupling between individual and collective pitch control [17]. As a result, load mitigation paid price is the increase in the actuator activity, but this control action has frequency of 1p (typically 0.2 Hz in our case), that's why it does not impose magnificent pressure on the pitch actuator. It also requires measuring the flapwise moment of each blade plus the rotor's azimuth angle. IPC synthesis as proposed in [17] is shown in Figure 9.

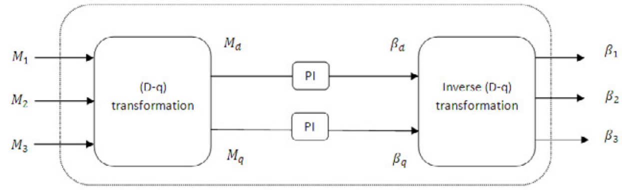

Fig. 9. IPC structure

This controller needs measuring the tip flapwise moment of each blade ($M_{1,2,3}$), these periodic loads are transformed to D-q frame by (park's d-q transformation [2]) as:

$$\begin{pmatrix} M_d \\ M_q \end{pmatrix} = \frac{2}{3}\begin{pmatrix} \cos(\Psi) & \cos(\Psi + \frac{2\pi}{3}) & \cos(\Psi + \frac{4\pi}{3}) \\ \sin(\Psi) & \sin(\Psi + \frac{2\pi}{3}) & \sin(\Psi + \frac{4\pi}{3}) \end{pmatrix}\begin{pmatrix} M_1 \\ M_2 \\ M_3 \end{pmatrix} \quad (33)$$

where M_d, M_q, Ψ are the direct (tilt) moment, quadratic (yaw) moment, and the rotor azimuth angle respectively. The tilt, and yaw moment are regulated by PI controllers. The resulted control action (β_d, β_q) is referred to the (D-q) frame. Last step will be transforming the control action to the rotating frame again by this inverse transformation (2/3 transformation):

$$\beta_{ipc=}\begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} = \begin{pmatrix} \cos(\Psi) & \sin(\Psi) \\ \cos\left(\Psi + \frac{2\pi}{3}\right) & \sin\left(\Psi + \frac{2\pi}{3}\right) \\ \cos\left(\Psi + \frac{4\pi}{3}\right) & \sin\left(\Psi + \frac{4\pi}{3}\right) \end{pmatrix}\begin{pmatrix} \beta_d \\ \beta_q \end{pmatrix} \quad (34)$$

5. Simulation Results

The proposed controller will be tested on FAST nonlinear model. This controller will be subject to difficult test by two ways. First, a stochastic wind model profile will be applied to the turbine. This wind profile covers all operating points. It presents a perfect disturbance to measure the controller performance under severe conditions. The turbine model will be tested against stochastic full field wind profile developed by The NREL TurbSim wind simulator [19]. Second, Unstructured model uncertainty will be presented by enabling more degree of freedoms in FAST model. Although our controller is based on 2 DOFs design model. It will be tested on nonlinear model with 6 DOFs that are typically mentioned in section (II). PI controller is tuned to guarantee good speed regulation. The controller is based on single linearized model derived at certain wind speed (V_w= 18m/s).Figure 10 shows the structure of the classic PI controller:

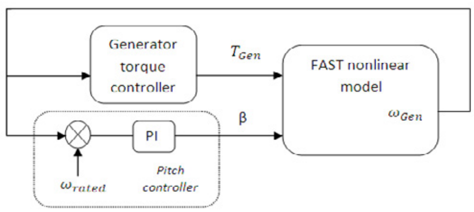

Fig. 10 Classic PI pitch controller

Comparison between the traditionally PI controller and the proposed controller is shown in Figure11.Speed regulation in both cases is compared in table 2.

Table 2 proves that the LMI controller gives better speed regulation as it managed to reduce the speed standard deviation significantly. It also reduced the maximum value of speed. This will prevent the mechanical overload on the drive train, and will increase the machine life time. On the other hand, the mean harvested power improved slightly, but the maximum power was reduced significantly. This will prevent the false shut down of the generator due to overloading, and keep it working within permissible rated values.

The comparison in table 3 shows the privilege for the (IPC) controller. The conventional PI controller is a collective pitch controller; it can't reduce the cyclic mechanical loads. The IPC managed here to reduce the cyclic loads significantly by alleviating the (1P) frequency loads. The strong standard deviation reduction ensures this. More important, the IPC managed to reduce maximum load significantly, and this will keep the flapwise moment in a safe side range of operation according to the turbine dynamics constrains mentioned in [1]. As a result, the maintenance cost will be diminished, and the life time of the turbine will increase.

Table 2. Speed, power data analysis

		PI	LMI
Generator speed	Max.	1298 rpm	1186 rpm
	Mean	1181 rpm	1172 rpm
	Std.	24 rpm	4 rpm
Electric power	Max.	5528 KW	5051 KW
	Mean	4892 KW	4913 KW
	Std.	271 KW	151 KW

Mechanical Load reduction is compared in table (3):

Table 3. Flapwise moment data analysis

		PI	IPC
Flapwise moment	Max	16460 KN.m	6447 KN.m
	Std.	2129 KN.m	649 KN.m

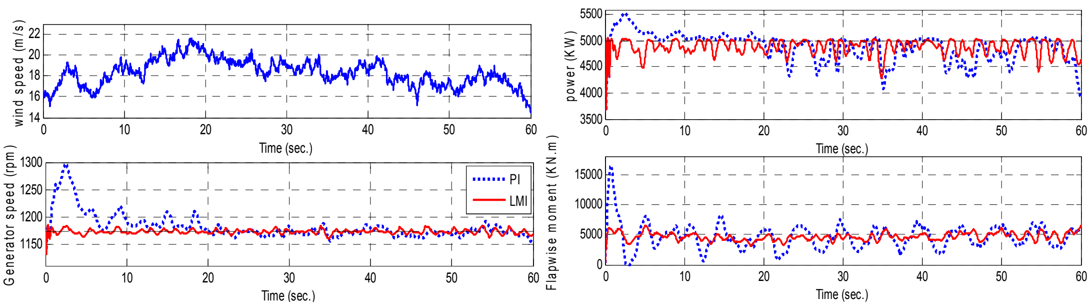

Fig. 11. Results of PI, proposed pitch controller

6. Conclusion

This paper has addressed the design of LMI-based robust CPC for large variable-speed variable-pitch wind turbines. The controller has been combined with IPC to reduce the mechanical loads. CPC has been first designed based on single design model, but the desired constrains were not fulfilled at all the operating points. As a result, a polytopic models approach has been considered. The design constrains have included H_∞ problem, H_2 problem, H_2/H_∞ trade-off criteria, plus pole clustering. The performance of the proposed decentralized controller has been compared to a classical PI controller. The comparison has shown that the proposed controller have achieved improvements in performance in terms of mechanical load reduction, speed regulation, and full load power harvesting.

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